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Anesthetic challenges and outcomes for procedures in the intraoperative magnetic resonance imaging suite: A systematic review.

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Abstract

Background and objective: Hybrid operating room suites with intraoperative magnetic resonance imaging enable image guided surgery in a fully functional operating room environment. While this environment creates challenges to anesthetic care, the effects on anesthetic adverse events and outcomes are largely unknown. This systematic scoping review aims to map the existing knowledge about anesthetic care in advanced imaging hybrid operating rooms.

Methods: A broad-based literature search was performed using the PubMed (Medline), Embase, Cochrane Library, Web of Science, and Google Scholar databases. References published in English between January 1994 and August 2017 were included. Quality of evidence was assessed using the GRADE guidelines.

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Conflicts of Interest: none

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Results: Forty-seven manuscripts were eligible for data collection. Adverse events were heterogeneously defined across 17 manuscripts and occurred in 0 to 100% (quality of evidence mostly very low). Monitoring difficulty was reported in 4 manuscripts of very low data quality. Interference between the magnet and the electrocardiogram was investigated in 2 manuscripts (quality of evidence low and very low, respectively). None of the reported events appeared to result in long-term patient harm. Author recommendations or a narrative review of the literature were provided in 40 manuscripts. Common safety concerns included lower equipment reliability, inaccessibility of the patient and airway, and the relative isolation of the suite (in relationship to other anesthesia care areas). Most authors also emphasized the importance of safety checklists, protocols, and provider training.

Discussion: While intraoperative magnetic resonance imaging hybrid operating rooms are increasingly utilized, the existing literature does not allow estimating adverse event rates in this location. Prospective studies quantifying the effect of the environment on anesthesia outcomes are lacking. Despite this, there is a broad consensus regarding the anesthetic and safety concerns. More research is needed to inform practice standards and training requirements for this challenging environment.

1. Introduction

Anesthesia care in a magnetic resonance imaging (MRI) environment poses unique challenges that are well described [1]. However, little evidence exists specific to MRI-guided surgical procedures, although several narrative review articles discuss far-reaching implications for anesthetic care [2–6]. Intraoperative MRI (iMRI) technology has steadily gained acceptance since its inception at the Brigham and Women’s Hospital in Boston, MA, in the early 1990s [7]. By early 2018, there were at least 43 iMRI suites in the US and 25 at international sites by early 2018 (personal communication with IMRIS, a market leader of hybrid surgical suites, 05/07/2018). Utilization of iMRI in the surgical arena presents multiple challenges. Clinical iMRI scanners most commonly have magnetic field strengths ranging from 0.2 Tesla (T) to 4.5 T. This static magnetic field is “always on” and exerting a strong force on ferromagnetic objects, potentially turning them into projectile missiles. Two other physical forces at play are radiofrequency and the pulsed magnetic field, both of which can generate heat in conducting materials, including the patient’s tissue. In addition to burn injuries, these forces can cause electrical interference and malfunction of medical devices [8]. Therefore, the iMRI operating room is usually radiofrequency-shielded, making wireless connections for equipment impossible. Introduction of a magnetic field within the surgical environment also necessitates modifications to the physical space and equipment, resulting in multiple changes to the usual workflow, communication, and patient care.

The use of iMRI technology is supported by the available evidence, suggesting a benefit to neurosurgical patients undergoing intracranial tumor resections [9–12]. Several other applications are being investigated, including epilepsy and breast cancer surgery [13,14]. These often complex and prolonged surgical procedures are associated with physiologic changes beyond what is commonly encountered in the diagnostic MRI suite.

Despite the growing body of evidence in support of iMRI for improved surgical outcomes, there is a paucity of literature regarding the anesthetic implications. In general, hybrid operating room suites, combining the technology of advanced imaging with the functions of a fully equipped surgical operating room, are viewed as a particularly challenging environment for provision of safe anesthetic care [15]. We conducted this systematic scoping review to investigate how the iMRI environment influences anesthetic care and outcomes. The objective was to map the existing knowledge about anesthesia in iMRI suites, identify knowledge gaps, and direct future research in this field.

2. Methods:

2.1 Search Strategy and Screening

2.1.1 Research question—We conducted a systematic scoping review [16–19] to identify articles describing the challenges facing anesthesiologists working in hybrid operating rooms with iMRI capability, with or without other imaging modalities. A *scoping review* is commonly defined as summarizing a “range of evidence in order to convey the breadth and depth of a field” [16] and involves the “synthesis and analysis of a wide range of research and non-research material to provide greater conceptual clarity about a specific topic or field of evidence” [17]. Our initial broad based search was intentionally designed to also identify manuscripts about computed tomography (CT) or positron-emission tomography with CT (PET-CT) hybrid suites, as we assumed that there would be significant overlap in safety protocols, especially because many centers combine all these imaging modalities with iMRI in the same hybrid suite. However, we found only one single reference reporting on anesthesia management for procedures involving intraoperative CT [20], and thus focused our evidence synthesis on iMRI. Hybrid angiography suites without iMRI capability were also excluded, as they do not have the same restrictions regarding equipment and communication and are often used for minimally invasive and low surgical risk procedures.

2.1.2 Identifying relevant studies—Prior to beginning the screening process, we established our study protocol, informed by the methodology for scoping reviews described by Levac et al., and the PRISMA-P guidelines (see appendix A) [16,21]. The overarching goal was to identify manuscripts related to factors affecting anesthetic care and outcomes in iMRI operating room suites. Our search strategy was designed to be broad based, consistent with the fundamentals of a scoping review [16]. To this end, a research librarian (HAJ) identified relevant databases and developed a comprehensive search strategy employing database-specific subject headings (e.g., MeSH, Emtree) and text words (see Appendix B). We searched for the intersection of two major themes: anesthesia and hybrid operating room, using variations and different spellings of the terms “anesthesia” and “intraoperative magnetic resonance imaging”, “tomography”, or “hybrid operating room” (see supplemental content, Appendix B, for full search strategy). We applied these search strategies to the PubMed (Medline), Embase, Cochrane Library, Web of Science, and Google Scholar databases. We did not impose any restrictions on publication type, but limited articles to those written in English and published between January 1, 1994, and August 24, 2017. This

epoch begins with the year when the first intraoperative MRI scan was performed and ends with the date our database search was completed [7,22].

2.1.3 Study selection—Three authors (HS, TLW, MSR) participated in the study selection process. The web application Rayyan (<https://rayyan.qcri.org/>) was used to facilitate the screening process [23]. Each reference underwent an initial screen of titles and abstracts by two independent reviewers. Articles were excluded if they did not address: 1) intraoperative MRI imaging, 2) hybrid imaging operating rooms, 3) surgical procedures of greater than low risk (i.e. diagnostic and percutaneous non-cardiac or non-vascular procedures were excluded), 4) human subjects, or 5) a topic of interest. We pre-defined “topic of interest” as any topic relevant to anesthesia planning, challenges/difficulties, complications/outcomes, patient safety/safety concerns, quality, human factors/team work, patient selection/pre-procedure screening, check lists, simulation and training, back-up and emergency planning, crisis management, equipment/operating room design factors, location implications, with the option to include other not *a priori* defined topics falling within the scope of challenges to patient care in a hybrid imaging operating room. Subsequently, the remaining references underwent full text review by two independent reviewers following the same criteria. When discrepancies regarding inclusion of manuscripts arose, the third reviewer was included in a consensus-finding discussion. Finally, we reviewed the reference lists of full-text articles chosen for inclusion and added manuscripts that had not yet been identified and met inclusion criteria.

2.2 Data extraction and synthesis

To extract data, we summarized the manuscripts’ content for each of the pre-identified topics of interest as well as for any other relevant topic in tabular format. For each manuscript, the article type, content, and data supporting the content were charted. Three authors (HS, TLW, MSR) reviewed the resulting data spreadsheet for completeness and consistency. Next, the included manuscripts were broadly categorized into data-containing and non-data-containing manuscripts. We abstracted information on outcomes and topics of interest from all data-containing manuscripts. Summary of findings tables were generated, and the evidence was graded according to the methodology described in the GRADE guidelines [16,24]. Non-data-containing manuscripts, along with any manuscript containing recommendations or a review of anesthetic care in the iMRI environment, were examined for recurring themes, recommendations, or statements. Those were identified and grouped according to overlying topic areas. The presence of each particular theme/statement was noted for all references in tabular format to visualize the extent of consensus among authors.

3. Results:

Our initial search yielded 6,796 manuscripts from Pubmed (Medline), Embase, Cochrane Library and Web of Science. An additional 100 references were included from Google Scholar (see figure 1). After removing duplicates, 4,460 manuscripts were screened using abstract review, with 143 remaining manuscripts undergoing full text review, resulting in 46 manuscripts finally included for data collection and analysis. One additional manuscript

from the reference list of an included paper was included, for 47 total manuscripts (see Figure 1).

The included manuscripts mainly consisted of informal (non-systematic) reviews (n=10) [2–6,25–29], institutional experiences (n=10) [30–39], and case series/retrospective studies (n=12) [40–51], with only a few prospective studies (n=4) [52–55]. We also included 11 references that were published only in abstract form [56–61] or case report format [62–66]. Original data pertinent to the topics of interest could be extracted from the case series/retrospective studies, prospective studies, and from 5 abstracts (see Table 1).

Stratified by imaging modality, the vast majority of manuscripts focused on iMRI alone (n=44) or on iMRI combined with angiography (n=3) [30–32]. The most commonly used operating room setup involved a mobile iMRI machine, but six manuscripts specifically discussed transfer of the anesthetized patient into a fixed MRI scanner [32,33,36,40,47,53]. We did not discriminate between the two settings in our data analysis due to the overall paucity of data and inability to address confounding variables. Most manuscripts discussed neurosurgical procedures (n=32) or addressed anesthetic concerns in general without differentiating a surgical specialty (n=13).

3.1 Adverse events during cases with iMRI

Seventeen manuscripts reported data on adverse events from a total of 2520 cases, which can be further divided into the following broad categories: adverse anesthesia or clinical events (reported in 12 manuscripts, including a total of 1955 cases) [40–46,53,55–58], MRI-related adverse events (reported in 7 manuscripts, including a total of 889 cases) [42,43,46–48,57,59], or technical problems (reported in 5 manuscripts, including a total of 535 cases) [47–49,51,53]. We did not examine surgical adverse outcomes or complications, even though those were addressed in some of the included manuscripts, because our research question focused on anesthetic considerations.

Adverse anesthesia or clinical events were heterogeneously defined; and no definition was provided in several manuscripts (see Table 2). On the one hand, “no adverse anesthesia events” were reported in 5 manuscripts. On the other hand, one author reported an adverse event in 100% of cases [55], using a broad definition that included inability to use the usual equipment and interference with monitoring. Monitoring difficulty was specifically noted in 4 manuscripts, and ranged from 4%, when “monitor dysfunctions” were encountered, to 100%, when electrocardiogram (ECG) interference was counted as adverse event. Beyond monitoring difficulty or deviation from standard practice to follow MRI-safety protocols, few clinical adverse events or complications were mentioned across the available literature, including cardiac arrhythmias, mild hypothermia, difficult tracheal intubation, delayed extubation, facial soft tissue swelling, and brachial plexus compression. Only one manuscript explicitly recorded hemodynamic changes in excess of 20% compared to baseline, which occurred during 90 of 580 scans (16 %) [56]. None of the 12 manuscripts examining adverse anesthesia events described a serious event resulting in long-term negative consequences to the patient. The existing literature did not allow us to estimate the incidence of significant clinical adverse events in iMRI environments, because of the inconsistent definitions and broad composite event categories, often resulting in the lack of a

numerator for a specific outcome. The relative risk compared to non-iMRI locations is also unknown, because most studies lack a comparison group.

Adverse events related to iMRI were investigated in 7 manuscripts, with 6 of those reporting no iMRI-related incidents (see Table 3). A small case series of 21 patients by Jankovski et al. reported 2 skin burns attributed to heat generation by iMRI, which instigated a modification of the institutional safety practices [47].

Technical problems were specifically mentioned in 5 manuscripts (see Table 4). The definition for those was again heterogeneous, from inability to perform the scan or difficulty with coil positioning to software problems causing imaging delays and problems during operating room table movement. One study demonstrated a significant decrease in the occurrence of technical problems in the last 100 of 300 consecutive patients, compared to the first 100 (3 vs. 31, $p < 0.001$) [48].

3.2 Duration of cases performed with iMRI

Fifteen manuscripts addressed the surgical or case duration of procedures with iMRI (see Table 5) [40,42,43,46–51,53–58]. Several definitions for those time periods were considered in the different studies as summarized in Table 5. Despite the heterogeneous definitions used, the authors consistently reported a long case duration for procedures with iMRI. Those including a comparison to non-imaging cases reported a prolongation of 57–122 minutes. The set-up time was 56–93 minutes, and the positioning time 20–88 min. The actual iMRI scan duration was measured in 6 manuscripts and accounted for about 30 minutes per scan, with large variation both within the same institution and among institutions with a reported range of 5–58 minutes.

3.3 Effects of iMRI on ECG monitoring

Two manuscripts were identified specifically looking for effects of the electrical noise generated by the iMRI on ECG monitoring [41,52]. Both reported detrimental effects of iMRI on the ECG, making ST segment analysis impossible once in the bore of the magnet and during an actual MRI scan (see Table 6).

3.4 Effects of iMRI on neuromuscular blockade

One single manuscript investigated the effects of iMRI on the onset, maintenance, and recovery of muscle relaxation action of vecuronium in 25 neurosurgical patients undergoing procedures with iMRI, compared to 25 controls in a regular OR [54]. The study concluded that iMRI prolonged the time for both the operation and infusion of muscle relaxant, caused an increase in core body temperature, and shortened the duration of clinical action of vecuronium by several minutes. The decreased duration of action was statistically significant; however, the change was small (TOF 90% after 63.4 $\pm$ 2.63 min in the iMRI cohort versus 69.4 $\pm$ 4.16 min in the non-iMRI cohort).

3.5 Awake craniotomy with iMRI

Five references reported considerations for awake craniotomies in an iMRI setting. Awake craniotomies are especially challenging in this environment, because direct assessment of

the patient is limited during an MRI scan, and routine physiologic monitors may not reliably work [56,63]. The largest case series by Kamata et al. was published only in abstract format and reported critical events during 365 awake craniotomies [56]. The other 4 references consisted of one abstract describing a single case [65], one case report [64], and 2 smaller case series describing the institutional experience with 42 and 7 cases, respectively [50,63]. The authors noted challenges related to patient positioning, the noise burden during scanning, and the added difficulty of anesthesia management in an iMRI environment while providing care to an awake but inaccessible patient with an unsecured airway.

3.6 Summary of expert opinion/consensus regarding anesthesia care in an iMRI operating room suite

Our literature search yielded few manuscripts with original data (see Table 1). In contrast, most of the included manuscripts reviewed challenges for safe anesthesia management in an advanced imaging operating room and made recommendations about how to optimally deliver anesthesia care in this environment. These recommendations are based on non-systematic reviews of the existing literature, often using extrapolation from studies of anesthetic care for diagnostic MRI, predating the evolution of iMRI. In addition, many authors described their institutional iMRI practice and gave expert advice on safety for procedures in this setting. We synthesized the most commonly discussed themes from 40 manuscripts about iMRI suites (see Figure 2). Aside from detailing specifics of anesthetic care in the iMRI setting, many authors noted safety concerns specific to the iMRI environment: There was wide agreement regarding the need for safety protocols and ferromagnetic object counts prior to moving the iMRI machine to the patient or transferring the patient into the scanner [3–6, 26–29, 32, 33, 36, 38, 43, 45, 55, 59–62]. Several manuscripts described a risk for dislodgment or disconnection of an airway or vascular access devices, typically associated with transfer into the scanner or from vibrations caused by the scanning process [2, 4, 6, 28, 33, 38, 39, 44, 46, 53, 55, 62, 64]. Another commonly voiced concern was that the available MRI-compatible physiologic monitors have limitations in their functionality [2–6, 25–29, 32–39, 43–47, 49, 51, 53, 55, 57, 59, 61, 64, 66]: electrocardiogram artifacts and poor ST segment monitoring ability were consistently reported, as was lack of MRI-safe temperature monitoring in earlier references. It was frequently stated that the MRI-compatible monitors were very sensitive to motion and other artifacts. In addition, many authors commented on the distance between the patient and the location of the anesthesia team and equipment, resulting in a need for extensions for the intravascular lines, breathing circuit, and gas sampling line [2–4, 6, 25, 26, 28, 30, 33–35, 37–39, 46, 49, 51, 55, 59, 61, 63, 66]. Several authors agreed that the increase in extensions and dead space can cause delays in intravenous or inhalational drug administration and recognition of a malfunction such as disconnection or obstruction of tubing, which is further compounded by the inability to readily assess the airway or vascular access sites during the procedure [2, 3, 5, 6, 26, 38, 39, 51, 55]. Exclusion criteria for patients deemed ineligible for iMRI environment were also commonly discussed. Typical exclusion criteria cited were patients with contraindications to MRI scanning (such as some implants and ferromagnetic foreign bodies), patients with significant coronary artery disease (due to limited ECG ischemia monitoring), small infants (due to difficulties resulting from dead space and temperature control), and obese patients (due to difficulty with positioning and inability to

fit into the scanner fully draped) [2, 4, 5, 26, 27, 29, 31, 32, 34, 35, 38, 39, 44–46, 49, 50, 55, 60, 63, 66]. The prolonged preparation time and case duration related to the complex set-up and extensive safety measures was frequently mentioned [6, 25, 28, 31, 32, 34, 35, 39, 42, 44, 50, 51, 55, 57, 59, 63, 65]. A few authors specifically commented on the unfamiliarity of the iMRI suite or distractions, including the noise burden [3, 6, 26, 29, 33, 34, 38, 39, 45, 46, 55, 61, 63, 64, 65]. Several demanded extra personnel, either as a designated safety person or to assist with airway/patient management during crisis due to the limited access to the patient and long distance from the anesthesia equipment [2, 5, 26, 31, 32, 38, 50, 55, 60]. The immediate availability of emergency equipment and a “safe” space or induction room without the restrictions of the iMRI room, were other commonly articulated concerns [3, 28, 31, 37–39, 44–46, 49, 50, 66]. Many authors agreed on the need for specific orientation or training requirements for any team member working in an iMRI suite [3–6, 26, 27, 29, 31, 36, 39, 45–47, 51, 61, 62]. Some authors recommended mock event trials and simulation training [3–6, 26, 27, 29, 31, 36, 38, 39, 45, 61, 62]. Many also commented on the relative isolation of the iMRI operating room suite, due to the limitations of pager and phone use, controlled access to the iMRI suite, as well as sometimes the remote location within the institution (including distance from other anesthetizing areas and the accompanying complement of experienced personnel) [2, 3, 5, 6, 29, 33, 35–37, 39, 43, 45, 49, 50, 61]. Considerations about patient routing from pre-operative location, transport to and from the iMRI suite, and to the post-operative recovery location were also discussed in several articles [3, 6, 25, 30, 32–35, 38, 39, 43, 45, 51, 53, 55, 61]. The importance of a ventilation and air filtration system, providing the same safety standards as a regular operating room, was discussed, particularly if the iMRI suite was also used for non-surgical (diagnostic or research) purposes [30, 32, 33, 39, 47, 53]. Cost considerations and ways to increase utilization of the suite to offset the significant financial investment of building an iMRI suite were also regularly debated [32, 33, 39, 46, 53].

4. Discussion:

This systematic scoping review was conducted to summarize the existing evidence about anesthetic care in iMRI operating rooms. In line with national and international guidelines regarding safe anesthetic care in a magnetic resonance imaging environment [1,67], we found a broad consensus regarding the need for specialized equipment, provider education, patient screening, and emergency preparedness. We identified recurring concerns related to limitations in the reliability or functionality of MRI-compatible equipment, the difficulty to directly assess airway and vascular access sites while the procedure is underway, the increased time requirement for case preparation and adherence to safety protocols, and the relative isolation of the iMRI suite.

While these concerns are shared by many authors, there are surprisingly little data about resultant adverse events or safety problems in the iMRI setting and about adverse patient outcomes related to the location. The notable exception is case duration, which was shown across multiple studies to be longer for procedures involving iMRI. Case length in an iMRI-suite has yet to be linked to adverse clinical outcomes, however long duration in standard operating rooms might be associated with higher risk for perioperative complications, such as pressure sores or surgical site infections [68,69].

Another anesthetic challenge that is backed by data-containing manuscripts is the difficulty to obtain reliable ECG monitoring due to ST segment changes [41,52]. This interference with ECG monitoring was also reported in a more recent simulation study [70]: Anesthesiologists were asked to interpret ECG monitoring strips subjected to simulated electrical interference. Interestingly and perhaps reassuringly, detection and identification of arrhythmias remained unchanged while electrical interference was present, but ST segment analysis was not attempted. One study included in the present review noted (benign) arrhythmias in several of their patients [41], which was not reported in other studies. It is unclear whether the arrhythmias were induced by the magnetic forces; but heart rate fluctuations for both diagnostic and intraoperative MRI have been previously described [56,71]. We found very few quantitative data on monitor artifacts or dysfunctions beyond ECG interference. There are many possible explanations, such as underreporting of sub-optimal equipment performance and inability to capture those events on a retrospective chart review. In addition, much of the presented evidence is derived from case series without a control group – so it is unclear whether any of the reported events are truly more common in iMRI settings compared to a “regular” operating room. A recent study utilizing data from the National Anesthesia Clinical Outcomes Registry (NACOR) about adverse anesthesia events in non-operating room locations found a higher rate of minor and major complications for radiology and cardiology locations compared to the regular operating room (but not for other non-operating room locations) [72]. Surprisingly, and in contrast to the findings suggested in the present review, monitoring and equipment problems were more likely in the operating room in this study.

Observational studies could quantify the effect of the relatively unfamiliar iMRI equipment and environment on patient care: Monitoring dysfunctions and delays in recognition and treatment of patient instability in iMRI locations compared to standard operating rooms could be prospectively assessed. Subjective provider comfort and distraction levels could be measured using survey methodology. Systematic tracking and sharing of near misses (in addition to adverse events) in iMRI locations would provide a resource for iMRI institutions to learn from each other and enable them to preemptively address known safety concerns, potentially decreasing the frequency of events during the initial learning period.

The discrepancy between the regularly verbalized concern about providing anesthesia care in the iMRI environment and the lack of data on adverse patient outcomes is curious, but not unique to the iMRI operating room: The rate of adverse outcomes for “off-site” locations has been difficult to assess, and may be lower or higher than in regular operating rooms, depending on the outcome and exact site studied [72–74]. A recent publication reports an increased risk for radiology locations, but it is unclear if hybrid iMRI operating rooms were included in their data base [72]. The present review could not identify any fatalities or near misses with a high chance for a poor outcome during > 2500 iMRI procedures from 17 manuscripts. While this could be due to underreporting or publication bias, it is also important to note that many iMRI centers mandate safety protocols, specific provider training, and presence of additional personnel in recognition of the inherent risks of patient care in iMRI locations. Therefore, the lack of reported poor outcomes may in part be a testament to the effectiveness of safety measures and the heightened vigilance exerted by iMRI providers.

The absence of high quality data linking anesthesia care in the iMRI environment with relevant outcomes is an important knowledge gap that has to be addressed. The current literature consists mostly of retrospective case series from single institutions. It is plausible that any complications during the initial learning period after opening the iMRI suite were underreported. A prospective study could provide high quality data comparing the rate of adverse events in the iMRI environment to a regular operating room environment. Such a study would require a control group of similar patients undergoing procedures in a regular operating room. However, since major adverse events are rare, such a study would need to include a high number of patients or risk to be vastly underpowered. The next best approach would be to utilize existing outcome databases with established categories and rating systems of adverse events: Several national and international registries collect data about rare events and complications related to anesthesia care, such as the National Anesthesia Clinical Outcomes Registry (NACOR) and Multicenter Perioperative Outcomes Group (MPOG). If these databases were to add an identifier for iMRI procedures, we would be able to more accurately estimate the rate and type of adverse events, which could shed some light on the nature of adverse events encountered in the iMRI environment.

5. Conclusion:

iMRI suites are a uniquely challenging environment because the physical forces of the strong magnetic field and radiofrequency add an additional layer of management complexity. Our systematic scoping review identified many areas of potential concern to anesthesiologists, but data on outcomes are lacking. Safe conduct of anesthesia in this environment requires a myriad of adjustments to “standard care”, which significantly affect case preparation and execution of the anesthetic. It remains to be seen if adverse events are more likely to occur in this environment, as surgery involving iMRI is becoming routine at many institutions. Systematic evaluation of adverse events and outcomes could inform iMRI-specific guidelines or standards of care, patient eligibility, and anesthesia provider training.

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Appendix A –: Research Protocol

Working title: Anesthetic challenges of procedures in advanced imaging hybrid operating rooms: A scoping review.

PROSPERO ID: (As a scoping review, this was not eligible for registration with PROSPERO.)

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Contributions:

The authors listed contributed to this research protocol.

Support:

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Introduction:

Rationale/Overarching goal:

To identify unique challenges and/or outcomes of performing surgical cases in advanced imaging hybrid operating rooms (MRI-OR, CT-OR, PET-OR), and/or to identify the knowledge gap regarding those challenges/outcomes.

This will direct future research efforts to further delineate challenges/outcomes and address specific knowledge gaps, ultimately leading to improvements in patient safety, quality of care, and process flow.

Research question:

PCC (Population/who; Concept/what; Context/which qualifiers):

P: Patients undergoing procedures of greater than low risk in a hybrid imaging OR

C: very broadly: challenges and factors affecting anesthesia planning and execution in this setting (see “Themes” listed below)

C: intentionally left open – but we will consider sub-questions to create context along the following themes:

Themes/Areas of interest:

We aim to identify papers related to factors affecting anesthesia planning, challenges/difficulties, complications/outcomes, patient safety/safety concerns, quality, human factors/team work, patient selection/pre-procedure screening, check lists, simulation/training, back-up plan/emergency plan/crisis management, equipment/OR design factors, location. In addition, themes not considered *a priori* may be added – keeping with this being a scoping review.

Methods:

Eligibility criteria:

PCC (see above)

Inclusion criteria:

- Study/paper must involve human subjects
- Location must be a hybrid imaging (MRI/CT/PET) operating room suite
- procedures performed must include “invasive surgery”, i. e. > low risk surgery.
- Reported outcomes/challenges/complications must be generalizable in the sense that knowledge about the themes listed above (or a newly identified area of interest) is gained. Thus, to be included in this review, the article cannot be about merely any technical aspect of a unique procedure or technique, but it has to consider this aspect within the setting of being performed in the hybrid OR.

- English language
- Publication time frame: 01/01/1994 – present. The first intraoperative prototype installed at Harvard in 1994, therefore earlier literature will not be relevant.

Information sources: We will use a variety of resources to conduct a broad review of the literature from the inception of intraoperative MRI imaging through present day. The search will include consideration reviews, case reports/series, clinical trials, retrospective analyses, opinion pieces, letters, practice advisories, prospective trials, and grey literature from conference proceedings and white papers.

Databases: MEDLINE, Embase, Web of Science, Cochrane Library, GoogleScholar. We will also conduct an ancestral search based on the reference lists of the papers included for review.

Search strategy:

We consulted a librarian to identify relevant databases and to create a broad search strategy inclusive of MeSH and keywords, intended to capture all articles falling at the intersection of anesthesia and intraoperative MRI/PET/CT.

Search strategies will be based on the MEDLINE search below (figure A.1), and adjusted accordingly to align with database-specific controlled vocabulary.

Medline query ID (consecutive numbers)	Search terms used
#6	Search (#1 AND #5)
#5	Search (#2 OR #3 OR #4)
#4	Search iMRI[tiab]
#3	Search (((MRI[tiab] OR Magnetic Resonance Imaging[tiab] OR tomograph*[tiab] OR Magnetic Resonance Imaging[mesh] OR Tomography, Emission-Computed[mesh] OR Tomography, X-Ray[mesh]))) AND (operat*[tiab] OR intraoperat*[tiab] OR Operating Rooms[mesh])
#2	Search (((Hybrid operating[tiab]) AND (room*[tiab] OR theat*[tiab])))
#1	Search ((Anesthesia[mesh] OR Anesthesiology[mesh] OR Anesthesiologists[mesh])) OR (Anesthes* OR anaesthes*)

Figure A.1:
MEDLINE Search strategy

Study Records

Data Management:

Two independent reviewers will use Rayyan (<https://rayyan.qcri.org/>) to facilitate the independent screening process. We will track reasons for exclusion in subfolders and will report exclusion criteria in the PRISMA flow diagram.

Selection process:

Two independent reviewers will perform an initial screen by reviewing the titles and abstracts, and perform the final screened by reviewing the full text of articles. A third reviewer will resolve discrepancies regarding inclusion of articles. We will base our screening on the exclusion criteria.

Exclusion criteria:

First round based on title/abstract

- not about MRI/CT/PET

- not about imaging OR intraoperative imaging suites
- not about surgical procedures of greater than minimal risk (i.e. we will exclude diagnostic and percutaneous non-cardiac or non-vascular procedures)
- not involving human subjects

2nd Round based on full text review:

Some papers may not have been identified during the first round of screening, but may still be excluded for those same reasons listed above after the full text review.

In addition, papers will be excluded if they are not about the themes of interest (such as merely reporting details/outcomes of a particular surgical technique).

Data to be extracted: see example (Table A.1)

Publication type

Type of paper (review, letter, case report, retrospective analysis, ...)

Type of imaging used (MRI, CT, PET, combination)

Type of surgery (intracranial, spine, intrathoracic, intraabdominal, any)

Primary topic of publication

Topic(s) relevant to our research interest

Other (new, potentially interesting) topics

Pertinent findings/points

Gaps in knowledge identified

Data collection process:

Two independent reviewers will then collect data for each of the included studies. Once we identify the studies to be included, we will pilot the process of extracting data using the data extraction table presented above and make modifications as needed.

Table A.1:

Data extraction spread sheet (draft version)

Reference, year of publication	Type of paper	Intraoperative Imaging modality	Type of surgery/intervention	Main topic(s)	“our” themes of interest	Other pertinent themes	Pertinent findings (author recommendation vs. consensus vs. practice guideline vs. result of original research)	Knowledge gaps
Berkow 2016	review	MRI	any	Challenges of MRI-Or magnetic field/MRI physics checklists team training	# 1, 2, 4, 7, 10	Physics of field etc.	Use of checklists and individual as well as team training maximizes patient and provider safety	Per authors: n/a per us: no evidence to support how team training affects safety

Themes: 1 = anesthesia considerations, 2 = challenges/difficulties, 3= complications/outcomes, 4= patient safety/safety concerns, 5 = quality, 6 = surgical considerations, 7 = human factors/team work, 8= patient selection/pre-procedure screening, 9 = check lists, 10 = simulation/training, 11 = back-up plan/emergency plan/crisis management, 12 = equipment/OR design factors

Data synthesis:

We will pre-identify anesthesia challenges and other areas of interest. We will also describe gaps in knowledge.

Grading of evidence: Because this is a scoping review rather than a typical systematic review, we will not grade the quality of evidence, unless references with specific outcomes data are identified. In those cases, grading will be performed for each outcome, according to the methodology described in the Grading of Recommendation Assessment, Development, and Evaluation (GRADE) system.[Guyatt 2011]

Appendix B –: Search Strategy and Result Overview**Table B.1:**

Summary of total search results

Database	Platform	Years covered	Date conducted	Number of results
PubMed (Medline)	PubMed	1946-current	August 24, 2017	2,199
Embase	Embase.com	1974-current	August 24, 2017	3,237
Cochrane Library	Wiley	Issue #, date Database of Systematic Reviews: Issue 8 of 12, August 2017 Cochrane Central Register of Controlled Trials : Issue 7 of 12, July 2017	August 24, 2017	121
Web of Science	WOS	1900-current	August 24, 2017	1,239

Database	Platform	Years covered	Date conducted	Number of results
Google Scholar	Scholar.google.com		August 24, 2017	100
Total				6,896
Total with dups removed				4,616
Total published since 1994				4,460

Table B.2:**PubMed (Medline) Search Process (Run: August 24, 2017)**

Search ID number	Search terms used	Number of results
#7	Search (#1 AND #5) Sort by: Relevance Filters: English	2199
#6	Search (#1 AND #5)	2628
#5	Search (#2 OR #3 OR #4)	83220
#4	Search iMRI[tiab]	315
#3	Search ((((((MRI[tiab] OR Magnetic Resonance Imaging[tiab] OR tomograph*[tiab] OR Magnetic Resonance Imaging[mesh] OR Tomography, Emission-Computed[mesh] OR Tomography, X-Ray[mesh]))) AND (operat*[tiab] OR intraoperat*[tiab] OR Operating Rooms[mesh])))	83057
#2	Search (((((Hybrid operating[tiab]) AND (room*[tiab] OR theat*[tiab])))))	168
#1	Search (((Anesthesia[mesh] OR Anesthesiology[mesh] OR Anesthesiologists[mesh])) OR (Anesthes* OR anaesthes*))	448122

Table B.3:**Embase Search Process (Last Run: August 24, 2017)**

Embase Session Results		
No.	Query	Results
#7	#1 AND #5 AND [english]/lim	3,237
#6	#1 AND #5	3,676
#6	#2 OR #3 OR #4	101,170
#4	imri:ti OR imri:ab	466
#3	(mri:ti OR mri:ab OR 'magnetic resonance imaging':ti OR 'magnetic resonance imaging':ab OR tomograph*:ti OR tomograph*:ab OR 'nuclear magnetic resonance imaging'/exp OR 'computer assisted omission tomography'/exp OR 'x-ray tomography'/exp) AND (operat*:ti OR operat*:ab OR intraoperat*:ti OR intraoperat*:ab OR 'operating room'/exp)	100,891
#2	('hybrid operating':ti OR 'hybrid operating':ab) AND (room*:ti OR room*:ab OR theat*:ti OR theat*:ab)	272
#1	'anesthesia'/exp OR 'anesthesiology'/exp OR 'anesthesiologist'/exp OR anesthes*:ti OR anesthes*:ab OR anaesthes*:ti OR anaesthes*:ab	431,773

The left column indicates the search ID number, the center column indicates the search terms used, and the right column indicates the number of results.

Table B.4:**Cochrane Search Process** (Last Run: August 24, 2017)

Search ID number	Search terms used	Number of results
#1	(Hybrid operating and (room* or theat*)):ti,ab,kw or ((MRI or Magnetic Resonance Imaging or tomograph*) and (operat* or intraoperat*)):ti,ab,kw or (iMRI):ti,ab,kw (Word variations have been searched)	3220
#2	(Anesthes* or anaesthes*):ti,ab,kw (Word variations have been searched)	45321
#3	#1 AND #2	121

Table B.5:**Web of Science Search Process**(Run: August 24, 2017)

# 7	1,239	#5 AND #1 Refined by: LANGUAGES: (ENGLISH) <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>
# 6	1,355	#5 AND #1 <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>
# 5	64,961	#4 OR #3 OR #2 <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>
# 4	394	TOPIC: (iMRI) <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>
# 3	64,025	TOPIC: ((MRI OR Magnetic Resonance Imaging OR tomograph*) AND (operat* OR intraoperat*)) <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>
# 2	852	TOPIC: (Hybrid operating AND (room* OR theat*)) <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>
# 1	177,851	TOPIC: (Anesthes* OR anaesthes*) <i>Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years</i>

The left column indicates the search ID number, the center column in blue the number of results, and the right column indicates the search terms used.

Table B. 6:**Google Scholar Search Process (Last Run: August 24, 2017)**

The first 100 results were selected and included.

Search ID number	Search terms used	Number of selected results
#1	(Anesthes* or anaesthes*) AND (((Hybrid operating) AND (room* or theat*)) OR (MRI OR Magnetic Resonance Imaging OR tomograph*) AND (operat* OR intraoperat*))	100

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Figure 1:
Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow
diagram of study selection process.

	Abernethy 2012	Achenbach 2002	Baner 2009	Bergsma 2009	Berkow 2016	Chen 2016	Choudhury 2014	Cox 2011	Daneshmandi 2011	Ellis 2014	Fonseca 2014	Fried 1998	Henrichs 2011	Henrichs 2014	Jankowski 2008	Makris 2014	Martinez 2000	McClain 2011	Pal 2013	Pasargahi 2008	Pasargahi 2011	Raboin 2014	Rap 2016	Rap 2017	Schmitt 2003	Tanaka 2009	Zhang 2011
Preparation and planning for an iMRI service																											
Training for iMRI staff	X	X	X	X	X	X						X	X	X		X	X		X	X	X	X	X	X	X	X	X
Simulation training	X			X	X	X					X	X	X			X	X		X	X	X	X	X	X	X	X	X
Patient selection and/or exclusion criteria	X	X	X	X		X					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cost, utilization, cost effectiveness	X									X						X								X	X		
Processes for iMRI cases																											
Transport to/ from iMRI suite	X	X	X	X	X	X		X	X	X	X		X			X				X	X	X	X	X	X	X	X
Team huddle/communication of plan											X					X	X	X		X	X	X	X	X	X	X	X
Ferromagnetic equipment count checklist	X	X			X	X	X				X	X	X			X	X	X		X	X	X	X	X	X	X	X
Procedure protocol or safety measures checklist	X				X	X	X	X				X	X	X		X	X	X		X	X	X	X	X	X	X	X
Safe positioning (e.g. avoidance of loops, no skin contact)			X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Emergency protocols/road map	X						X		X							X				X							
Structural requirements and considerations																											
Additional safety personnel needed							X				X	X	X	X	X	X	X				X						
Remoteness/isolation of the iMRI suite	X	X	X	X	X		X	X							X	X				X	X	X	X	X	X	X	X
Restricted access needed, creates challenges	X				X	X	X				X	X	X		X				X	X	X	X	X	X	X	X	X
Ventilation/sterility considerations	X								X	X					X	X											X
Need for MRI compatible anesthesia equipment	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Need for extensions and/or deadspace in circuit or lines	X	X	X	X							X	X	X	X		X										X	
Induction room/safe room								X			X	X						X		X		X	X	X	X	X	X
Availability of emergency equipment	X	X					X				X				X				X		X						X
Safety and risk considerations																											
Prolonged set up and case duration		X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Distance from patient; limited access to airway/vascular sites	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dislodgement/disconnection risk (lines/airway)	X				X			X	X	X			X	X	X	X	X								X	X	X
Limitations of MRI compatible equipment: artifacts, unreliability, limited ECG analysis	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Temperature: limited ability to heat room and/or limited ability for temperature monitoring	X	X	X								X	X	X	X	X	X	X	X	X					X	X	X	X
Distractions and (un)familiarity with equipment/location	X	X									X													X	X	X	X
Noise burden (to patient and/or care team)	X	X	X	X							X	X	X						X	X	X	X	X	X	X	X	X
Communication limitations (pager/cell /phone)					X							X	X						X	X							

Figure 2:
Strength of the consensus on preparation, processes, requirements, and safety considerations affecting anesthetic care in intraoperative magnet-resonance imaging (iMRI) suites. For each manuscript, the presence of a particular theme is noted with “X”. Abbreviations: iMRI: intraoperative magnet-resonance imaging; ECG: electrocardiogram.

Table 1:**Manuscript types of included references.**

Type	n	Reference name
Non-systematic review	10	Archer/Manninen 2002, Berkow 2016, Foroglou 2009, Henrichs 2011, Henrichs 2014, Manninen 2000, McClain 2011, McClain 2014, Pal 2013, Porteous 2014
Institutional experience, expert opinion, or text book chapter	10	Abernethy 2012, Bergese 2009, Berkenstadt 2009, Cherkashin 2016, Cowperthwaite 2017, Darakchiev 2005, Ellis 2014, Fried 1996, Matsumae 2007, Tan/Goh 2009
Case series or retrospective study*	12	Ahmadi 2016, Archer/McTaggart 2002, Barua 2009, Birkholz , Choudhri 2014, Cox 2011, Fried 1998, Jankovski 2008, Maldaun 2014, Raheja 2015, Rahmatulla 2012, Schmitz 2003
Prospective study (with or without control)^a	4	Dzwonczyk 2009, Fomekong 2014, Guo 2013, Iturri-Clavero 2016
Abstract only^b	6	Kamata 2016, Panigrahi 2008, Panigrahi 2012, Rao 2012, Raymer 2017, Ruskin 2017
Case report	5	Chowdhury 2017, Peruzzi 2011, Takroui 2010, Tan/Leong 2009, Zheng 2011

^a: All these references contain original data which are summarized in the results and/or incorporated into the summary of findings tables.

^b: All except Raymer 2017 and Ruskin 2017 contain original data which are summarized in the results and/or incorporated into the summary of findings tables.

Table 2:

Summary of findings for adverse anesthesia or clinical events in iMRI suites.

Study (author and year)	Description <i>Magnetic Field Strength in Tesla (T)</i>	Incidence of outcome	N (included cases)	Data quality GRADING (reason)	Critique/comments
Ahmadi 2016	Retrospective chart review that identified anesthesia complications for patients undergoing intracranial surgery with iMRI compared to procedures without iMRI. (1.5 T)	No adverse anesthesia event reported in either group	1126 (516 in iMRI group, 610 controls)	VERY LOW (observational, nonrandomized, no control of confounders between cohorts)	Adverse anesthesia event not defined. Patients in this study were transferred between the OR and adjacent scan room. The authors did not report about transport problems.
Birkholz 2004	Observational study of impact of electrical interference and ECG analysis. This study did not explicitly report on adverse events. (1.5 T)	3 Arrhythmias 3 Arrhythmia-type artifacts	19	LOW (observational)	We considered the reported true and artifactual arrhythmias relevant clinical events: supraventricular tachycardia (n=1), supraventricular extra beats (n=2), and artifactual ventricular arrhythmia (n=1), artifactual ventricular fibrillation (n=1), artifactual atrial flutter (n=1).
Choudhri 2014	Retrospective study that assessed primarily surgical difficulties for pediatric neurosurgical patients undergoing iMRI procedures. (3 T)	No adverse anesthesia event	168	VERY LOW (observational, no control group)	Adverse anesthesia event not defined.
Cox 2011	Retrospective study that described clinical challenges and anesthesia outcomes in 98 pediatric patients undergoing 105 iMRI procedures over 10 years. These patients were transferred to a pediatric hospital close-by for postoperative care. (1.5 T)	No adverse anesthesia event 4 clinical complications 1 safety breach not resulting in harm	105	VERY LOW (observational, no control group)	Adverse anesthesia event not defined. Authors reported no anesthesia event, 4 clinical events (2 postoperative seizures, 1 swollen lip, 1 inflamed ear) and 1 safety event resulting in no harm (ferromagnetic clamp left in the field during MRI scan).
Fomekong 2014	Analysis of pituitary microsurgery with iMRI, primarily focused on surgical considerations. (3 T)	4 anesthesia events: - 3 patient monitor dysfunctions, - 1 unplugged IV line,	73	VERY LOW (observational, no control group)	Anesthesia events were among 17 reported "technical problems" (see also later in Table 4). It is unclear if the 17 described problems occurred during 17 separate procedures, or whether one patient experienced >1 problem.
Fried 1998	Case series that detailed the first endoscopic sinus surgery procedures in the iMRI suite at the author's institution. (0.5 T)	No adverse anesthesia event	12	VERY LOW (observational, no control group)	Adverse anesthesia event not defined.
Iturri-Clavero 2016	Review of anesthetic considerations for intracranial iMRI procedures. Prospective study of incidents and time requirements during cases using low-field iMRI compared to controls without iMRI. (0.15 T)	Anesthetic incidents occurred during all iMRI cases (n=109). Brachial plexus compression in all lateral and prone cases (no n provided), but no postoperative neurologic damage.	159 (109 for iMRI, 50 control)	VERY LOW (observational, no control of confounders between cohorts, possibly incomplete reporting)	Anesthetic incident was very broadly defined and included change from routine practice (including avoidance of intubating stylet or metal-reinforced endotracheal tubes), interruption of monitoring, and interference with monitoring. The rate of incidents for the control group was not reported.
Kamata 2016	Case series about critical events during awake craniotomy cases using iMRI, specifically during scan sequences in patients with an unsecured airway.	21 critical events 90 scans with cardiovascular changes Monitoring disruptions for:	580 scans (in 365 patients)	VERY LOW (observational, no control group)	Published in abstract form only. 21 critical events were observed: general convulsive seizure (n=6), respiratory arrest (n=2), nausea and vomiting (n=7), and emotional incontinence (n=9). No cardiac arrest or accidental death

Study (author and year)	Description <i>Magnetic Field Strength in Tesla (T)</i>	Incidence of outcome	N (included cases)	Data quality GRADING (reason)	Critique/comments
	<i>(field strength not specified)</i>				
		- blood pressure - heart rate - pulse oximetry - respiratory rate			occurred. Cardiovascular changes of >20% deviation from pre-scan baseline occurred during 90 scans: hypertension (n=32), tachycardia (n=58), hypotension (n=26), bradycardia (n=15). Monitoring disruptions occurred for BP and HR monitoring (n=2 each), and for SpO2 monitoring (n=25). Respiratory rate monitoring was used during only 175 scans.
Panigrahi 2008	Case series about anesthetic challenges and operative advantages of intracranial iMRI procedures. (1.5 T)	2 difficult intubations 4 delayed extubations ECG artifacts "quite often"	112	VERY LOW (observational, no control group)	Published in abstract form only. Adverse anesthesia event was defined as difficult intubation or delayed extubation. Delayed extubation was attributed to "prolonged anesthesia and hypothermia".
Panigrahi 2012	Retrospective analysis of anesthesia implications of intracranial iMRI cases. (1.5 T)	4 difficult intubations 4 cases of delayed emergence	388	VERY LOW (observational, no control group)	Published in abstract form only. Anesthesia complication was defined as difficult intubation, delayed emergence, and hypothermia. May include the 112 cases from prior abstract, but did not provide date range for the newer study.
Rahmatulla 2012	Overview of safety considerations for iMRI environment and retrospective assessment of the first intracranial iMRI cases over 29 months at the author's institution. (1.5 T)	No adverse event	120	VERY LOW (observational, no control group)	Adverse event was not defined. The authors mentioned that potential safety events discovered by check lists and safety protocols were not tracked, so their incidence was unknown.
Schmitz 2003	Case series about anesthesia for initial neurosurgical iMRI cases at the author's institution. (1.5 T)	1 case of hypothermia leading to delayed extubation	80	VERY LOW (observational, no control group)	Adverse anesthesia event not defined. Authors stated "no adverse event" but do report 1 case of hypothermia.

Abbreviations: iMRI: intraoperative magnet-resonance imaging; OR: operating room; ECG: electrocardiogram; BP: blood pressure; HR: heart rate; SpO2: pulse oximetry.

Table 3:
Summary of findings for adverse magnet-resonance imaging related problems in iMRI suites.

Study (author and year)	Description <i>Magnetic Field Strength in Tesla (T)</i>	Incidence of outcome	N (included cases)	Data quality GRADING (reason)	Critique/comments
Choudhri 2014	Retrospective study that assessed primarily surgical difficulties for pediatric neurosurgical patients undergoing iMRI. (3 T)	No adverse MRI-related event	168	VERY LOW (observational, no control group)	Authors collected MRI-associated data including amount of intravenous contrast administered and “any MRI-imaging related complication”.
Cox 2011	Retrospective study that described clinical challenges and anesthesia outcomes in 98 pediatric patients undergoing 105 iMRI procedures over 10 years. These patients were transferred to a pediatric hospital close-by for postoperative care. (1.5 T)	No adverse MRI-related event	105	VERY LOW (observational, no control group)	Authors stated in the discussion that there was “no significant morbidity attributable to [...] the iMR environment”.
Jankovski 2008	Description of development of the neurosurgical iMRI suite and case series describing the first intracranial procedures in the iMRI suite. (3 T)	No ferromagnetic accidents, 2 burns (1 intergluteal and 1 chest)	21	VERY LOW (observational, no control group)	Small case series with frank discussion of various problems encountered (see below for technical problems).
Panigrahi 2008	Case series about anesthetic challenges and operative advantages of iMRI procedures. (1.5 T)	No ferromagnetic accident	112	VERY LOW (observational, no control group)	Published in abstract form only.
Raheja 2015	Retrospective analysis of predominantly surgical outcomes of the first consecutive procedures in the iMRI suite. Cases were analyzed and compared in 3 chronologic subgroups. (1.5 T)	No adverse MRI-related event	300	LOW (observational, no adjustment for confounders)	Analysis of 3 chronologic subgroups showed “learning curve” for process flow.
Rao 2012	Case series over 2 years about anesthesia considerations for intracranial iMRI procedures. (field strength not specified)	No adverse MRI-related event	103	VERY LOW (observational, no control group)	Published in abstract form only. Reported “no significant adverse events related to the iMRI environment”.
Schmitz 2003	Case series about anesthesia for initial neurosurgical iMRI cases at the author’s institution. (1.5 T)	No adverse MRI-related event	80	VERY LOW (observational, no control group)	Authors reported no ferromagnetic accidents or “any untoward events resulting from the high magnetic field”.

Abbreviations: iMRI: intraoperative magnet-resonance imaging.

Table 4:

Summary of findings for technical problems in iMRI suites.

Study (author and year)	Description <i>Magnetic Field Strength in Tesla (T)</i>	Incidence of outcome	N (included cases)	Data quality GRADING (reason)	Critique/comments
Archer/McTaggart et al. 2002	Retrospective case-control study of anesthetic aspects of craniotomy procedures in the iMRI suite compared to the conventional OR. (1.5 T)	No treatment failures	152 (76 per cohort)	LOW (observational, matching of cohorts takes only surgical/anatomical factors into account)	Reported "no treatment failures", defined as "the requirement to limit the anesthetic or operative procedure because of technical problems involving the theatre".
Barua 2009	Case series that detailed anesthesia considerations for intracranial iMRI procedures, set-up time and surgical results. (0.15 T)	Unable to perform iMRI scan in 3 cases.	65	VERY LOW (observational, no control group)	MRI could not be performed due to body habitus and positioning (n=2) and due to tumor location not amenable to high quality scanning with low field scanner (n=1).
Fomekong 2014	Analysis of pituitary microsurgery using iMRI, primarily focused on surgical considerations. (3 T)	13 problems: - 11 surgical table blockades, - 1 MRI software bug, - 1 surface coil malposition	73	VERY LOW (observational, no control group)	See above. A total of 17 problems were reported, which included anesthesia events. It is unclear if the 17 described problems occurred during 17 separate procedures, or whether one patient experienced >1 problem.
Jankovski 2008	Description of development of the neurosurgical iMRI suite and case series describing the first 21 patients undergoing intracranial surgery in the iMRI suite. This suite includes a special operating room table with an MRI-compatible table top, which moves along tracks into the scan room and then slides onto the MRI table. (3 T)	16 technical and transfer-related issues, 10 of which prolonged the case for at least 10 minutes.	21	VERY LOW (observational, no control group)	Small case series with frank discussion of technical problems encountered: 4 cases with delays due to scan room not yet available (used for non-OR scans), 4 cases with head positioning too high causing minor imaging artifacts, transfer table blockade (n=1), MRI table blockade (n=1), coil unplugged (n=2), coil position artifact (n=1), metal artifact (n=1), MRI software bugs (n=2). The authors described a learning curve without providing actual data for this observation: surgical table blockade occurred "initially frequently" until the problem was identified and fixed.
Raheja 2015	Retrospective analysis of predominantly surgical outcomes of the first consecutive procedures in the iMRI suite. Cases were analyzed and compared in 3 chronologic subgroups (A, B, and C). (1.5 T)	38 technical problems overall, with decreasing incidence: 31 for group A, 4 for group B, 3 for group C; p<0.001 between A and C Unable to use iMRI in 11 patients due to technical problems.	300	LOW (observational, no adjustment for confounders)	Authors report a decreasing rate of technical difficulties over time. Technical difficulty was defined as "complications related to MRI machine, navigation, automatic registration, non-availability of MRI compatible ECG electrodes, operating table malfunction, microscope screen malfunction, planning software, image transfer, air conditioner related and high humidity".

Abbreviations: iMRI: intraoperative magnet-resonance imaging; MRI: magnet-resonance imaging; OR: operating room; ECG: electrocardiogram.

Table 5:

Summary of findings for case duration in iMRI suites.

Time measured	Definitions used	Duration mean $\pm$ SD or median (range) (minutes)	Study (author and year)	N (included cases)
Case Duration	time of the first vital signs recording in the anesthetic record to leaving the OR: OR entry to exit: total anesthesia time: time of total operation, not further defined: OR entry until skin closure: induction to pin removal: induction to extubation or operating room exit if the patient remained intubated:	407 $\pm$ 143 for iMRI and 285 $\pm$ 122 for controls (p<0.001) 428 $\pm$ 143 439 (185–710) mean 306 (range 210–460) 432.6 $\pm$ 15.57 for iMRI, 369.2 $\pm$ 19.85, p <0.001 458 min for iMRI and 387 min for control (p<0.001) 200–450 (no mean provided) 383 $\pm$ 123 for the first 100 patients and 328 $\pm$ 122 for the last 100 patients of 300 consecutive cases (p=0.007)	Archer/McTaggart 2002 Choudhri 2014 Cox 2011 Panigrahi 2012 Guo 2013 Iturri-Clavero 2016 Panigrahi 2008 Raheja 2015	152 (76 per cohort) 168 104 388 50 (25 iMRI/25 controls) 159 (109 iMRI, 50 controls) 112 300 (100 in each cohort)
Induction Time	from OR entry until ready for positioning:	84 for iMRI, 78 for control (no difference)	Iturri-Clavero 2016	159 (109 iMRI, 50 controls)
Set-up Time	intubation to incision: OR entry to incision: induction to incision:	mean 93 (range 30–180) 91 $\pm$ 40 mean 56 min (no range provided)	Barua 2009 Choudhri 2014 Panigrahi 2012	65 168 388
Positioning Time	end of induction time to incision: time of pin application until "patient was shifted back after preoperative MRI":	88 for iMRI, 30 for control (p<0.001) 20–60 (no mean provided)	Iturri-Clavero 2016 Panigrahi 2008	159 (109 iMRI, 50 controls) 112
Surgery Time	skin incision to closure: not further defined:	255 $\pm$ 10.6 for iMRI and 186 $\pm$ 125 for controls; longer by 57 $\pm$ 16 (p 0.01). 316 $\pm$ 130 284 for iMRI, 276 for control (no difference) mean 7.3 h (range 4.0–13.9) 245 $\pm$ 117 for the first 100 patients and 244 $\pm$ 107 for the last 100 patients of 300 consecutive cases (p=0.83) median 239 (69–565)	Ahmadi 2016 Choudhri 2014 Iturri-Clavero 2016 Maldaun 2014 Raheja 2015 Cox 2011	1126 (516 in IMRI group, 610 controls) 168 159 (109 iMRI, 50 controls) 42 300 (100 in each cohort) 104
iMRI Time ^a	time to complete the iMRI:	53 $\pm$ 11 29.4 $\pm$ 13.6 mean 34.1 (range 19–68) 21 mean 25.3 (range 5.3–58.0) 10–30min	Cox 2011 Fomekong 2014 Jankovski 2008 Kamata 2016 Maldaun 2014 Schmitz 2003	220 scans (105 cases) 73 26 scans (21 cases) 580 scans (365 cases) 42 80

Abbreviations: SD: standard deviation; iMRI: intraoperative magnet-resonance imaging; OR: operating room.

^a: iMRI acquisition time depends on the imaging sequences used. The following sequences were reported: Fomekong 2014: T1-weighted sagittal, T1-weighted coronal and T2 weighted coronal, all with fast spin-echo (FSE) technique; Jankovski 2008: T1- and T2-weighted fast spin echo, fast fluid-attenuated inversion recovery sequences, with additional echo planar imaging, spin echo, diffusion-weighted and time-of-flight phlebogram as needed; Maldaun 2014: T1-weighted spin echo, T2-weighted turbo spin echo, FLAIR, diffusion tensor imaging (DTI), and diffusion-weighted imaging (DWI). MRI sequences were not specified in the manuscripts by Cox, Kamata, and Schmitz.

Table 6:

Summary of findings for electrocardiogram limitations in iMRI suites

Study (author and year)	Description and Methods	Findings	N (included cases)	Data quality GRADING (reason)	Critique/comments
Birkholz 2004	Observational study that compared the immediate preoperative ECG tracings (obtained outside of MRI-OR) with the ECG tracings inside the MRI-OR with table in operating position, and with those obtained once inside the bore of the magnet, before and during the scan. The monitor used was the Invivo Omnitrak 3150 ^a .	Normal baseline ECG in all patients and no changes in scanner room outside 200 G line (n=19). Inside scanner/Static field: ST analysis impossible for all 19 patients. 10 patients with p wave disturbance/loss. 15 patients with "u wave" type change. During scan: ST analysis impossible for all 19 patients. "Some" R waves were undetectable. 3 arrhythmia-type artifacts occurred (1 each for resembling ventricular arrhythmia, ventricular fibrillation, atrial flutter).	19 patients with several ECGs each.	LOW (observational)	This study described ST alterations and artifacts with additional peaks and dips while inside the scanner. The amplitude of alterations differed between patients. The authors suggested characteristic changes depending on MRI sequence, with T2-weighted HASTE and EPI sequences yielding the most significant QRS distortions. 3 patients had true arrhythmias which could still be detected despite the artifacts (not reported whether those occurred inside the scanner or elsewhere).
Dzwonczyk 2009	Experimental evaluation of how interference generated by a low-field iMRI system affected the Veris MR monitor ^b . 1. Comparison of analogue waveforms on the vital sign monitor prior to and during iMRI scans in patients undergoing craniotomies. 2. An ECG simulator was connected to the Veris MR monitor and the input and output signals from each filter were evaluated.	1. Noise generated by the iMRI system during a scan did not interfere with blood pressure, plethysmography, respiratory CO ₂ , or agent signal during an MRI scan, however did add a substantial amount of noise to the ECG signal. 2. Filters changed ECG wave morphology, particularly in the t-wave suppression modes (t-waves are diminished).	no N specified	VERY LOW for 1, LOW for 2 (observational)	This study is limited by incomplete reporting (no number of patients/measurements provided).

^a: Omnitrak 3150 (Invivo Inc., Gainesville, FL, USA).^b: Veris MR monitor (Medrad Inc., Indianola, PA, USA).

Abbreviations: iMRI: intraoperative magnet-resonance imaging; ECG: electrocardiogram; RBBB: right bundle branch block; LBBB: left bundle branch block.